Hyper-Kamiokande Physics Opportunities

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Abstract

We propose the Hyper-Kamiokande (Hyper-K) detector as a next generation underground water Cherenkov detector [1]. It will serve as a far detector of a long baseline neutrino oscillation experiment envisioned for the upgraded J-PARC beam, and as a detector capable of observing, far beyond the sensitivity of the Super-Kamiokande (Super-K) detector, proton decays, atmospheric neutrinos, and neutrinos from astrophysical origins. The current baseline design of Hyper-K is based on the highly successful Super-K detector, taking full advantage of a well-proven technology. Hyper-K consists of two cylindrical tanks lying side-by-side, the outer dimensions of each tank being $48(W) \times 54(H) \times 250(L)\ m^3$. The total (fiducial) mass of the detector is 0.99 (0.56) million metric tons, which is about 20 (25) times larger than that of Super-K. A proposed location for Hyper-K is about 8 km south of Super-K (and 295 km away from J-PARC) at an underground depth of 1,750 meters water equivalent (m.w.e.). The inner detector region of the Hyper-K detector is viewed by 99,000 20-inch PMTs, corresponding to the PMT density of 20% photo-cathode coverage (one half of that of Super-K).

The Hyper-K project is envisioned to be completely open to the international community. The current working group contains members from Canada, Japan, Spain, Switzerland, Russia, the United Kingdom and the United States. This set of three one-page whitepapers describes the opportunities for future physics discoveries at the Hyper-K facility with beam, atmospheric and astrophysical neutrinos.

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Exploring Neutrino Properties with Atmospheric Neutrinos

In the late nineties, atmospheric neutrinos measured in the Super-Kamiokande detector provided the first definitive evidence that neutrinos had mass and that the mass states mixed to make the well known flavor states [7]. Atmospheric neutrinos remain an important probe of neutrino oscillations, and the large statistics sample from the one-half megaton Hyper-K will offer an unprecedented opportunity to study them in detail. Atmospheric neutrinos exist in both neutrino and anti-neutrino varieties in both muon and electron flavors. Approximately 1,000,000 events are expected to be collected in a 10 year period. The large value of θ_{13}, along with the neutrino versus anti-neutrino dependent matter resonance effect in the earth opens up the study of oscillation driven electron neutrino appearance. The oscillation effect in the electron neutrino flux have been analytically calculated [8] as:

$$\begin{aligned}\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \quad \approx \quad & P_2 \cdot (r \cdot \cos^2\theta_{23} - 1) \\ & - r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2) \\ & + 2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1) \end{aligned} \tag{1}$$

where we call the first, second, and third terms the "solar term", "interference term", and "θ_{13} resonance term", respectively. P_2 is the two neutrino transition probability of $\nu_e \to \nu_{\mu,\tau}$ which is driven by the solar neutrino mass difference Δm^2_{21}. R_2 and I_2 represent oscillation amplitudes for CP even and odd terms. For anti-neutrinos, the sign of the δ should be changed. Additionally, the modified probabilities for P_2, R_2, I_2 are obtained by replacing the matter potential $V \to -V$ (see [8] for details). The electron appearance effect along with precision measurements of muon disappearance [9] and tau appearance [10] will allow Hyper-K to probe the octant of θ_{23} oscillation, the mass hierarchy and CP violation phase.

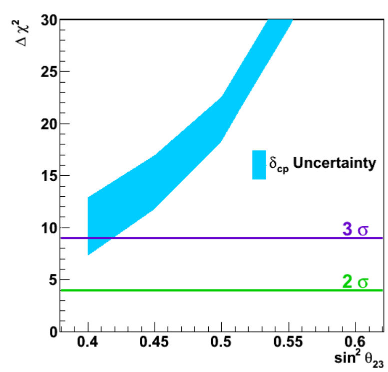

Figure 3: The sensitivity to the mass hierarchy as a function of θ_{23} with θ_{13} fixed at $\sin^2 2\theta_{13} = 0.098$ (NH case).

A full Monte Carlo and reconstruction study using Super-Kamiokande tools has determined that the expected significance for the mass hierarchy determination is more than 3σ provided $\sin^2\theta_{23} > 0.4$. We expect to be able to discriminate between $\sin^2\theta_{23} < 0.5$ (first octant) and > 0.5 (second octant) at the 3σ level if $\sin^2 2\theta_{23}$ is less than 0.99. For all values of δ, 40% of the δ range can be excluded at three sigma assuming that $\sin^2\theta_{23} > 0.4$. All of these results are obtained using atmospheric neutrinos alone. In combination with the JPARC beam they can be even more tightly constrained. As an example, figure 3 demonstrates the sensitivity to the mass hierarchy as a function of θ_{23} with θ_{13} fixed at $\sin^2 2\theta_{13} = 0.098$ for the case of the normal hierarchy.

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